Tracing Cosmic Evolution with Galaxy Clusters – Sesto Pusteria
ASP Conference Series 2002

Frequently Asked Questions on the Luminosity–Temperature relation in Groups and Clusters

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Abstract. Efforts to understand the deviation of the L–T relation from a simple scaling law valid for clusters and groups have triggered a number of interesting studies on the subject. Techniques and approaches differ widely but most works agree on the important role played by gas cooling and heating sources like AGNs and SNe. Observations set useful constraints on the evolution of the intracluster medium (ICM): a 100KeV/cm^2 entropy floor in the core of groups and about 5–15% of baryons being converted into stars. However, essential details like the nature of the dominant heating mechanism and the quantitative importance of cooling still need to be addressed. I suggest that a new generation of high resolution N-body simulations and a quantitative comparison of results between different approaches is required to improve results and increase our understanding of the problem.

1. Q: What are the Theoretical Expectations for the L–T relation?

The first attempt to model the ICM in the framework of the hierarchical scenario assumed its thermodynamical properties to be entirely determined by gravitational processes, like adiabatic compression during collapse and shock heating (Kaiser 1986). If no characteristic scales are present in the underlying cosmology (i.e., Einstein–de-Sitter cosmology and power–law shape for the power spectrum of density perturbations), this model should predict hot gas within rich clusters to look the same as within poor groups, since gravity in itself does not have characteristic scales. Under the assumptions of emissivity dominated by free–free bremsstrahlung and of hydrostatic equilibrium of the gas, this model predicts $L_X \propto T^2(1+z)^{3/2}$ for the shape and evolution of the relation between X–ray luminosity and ICM temperature (also Eke, Navarro & Frenk 1998). Furthermore, if we define the gas entropy as $S = T/n_e^{2/3}$ (n_e: electron number density; e.g., Eke et al. 1998), then the self–similar ICM has $S \propto T(1+z)$.

2. Q: What are the observational Constraints?

However, soon the simple model described above failed to account for several new observational facts: (a) the L_X–T relation for nearby clusters is steeper than predicted, with $L_X \propto T^{\sim 3}$ for $T > 2$ keV clusters (e.g., David et al. 1993; White, Jones & Forman 1997; Allen & Fabian 1998; Markevitch 1998); with

a possible further steepening at the group scale, $T < 1$ keV (Ponman et al. 1996; Helsdon & Ponman 2000); (b) no evidence of evolution for its amplitude has been detected out to $z > 1$ (e.g., Fairley et al. 2000; Della Ceca et al. 2001; Borgani et al. 2001a); (c) the gas density profiles in central regions of cooler groups is relatively softer than for hotter cluster and, correspondingly, the entropy is higher (e.g., Ponman, Cannon & Navarro 1999; Lloyd–Davis et al. 2000). Observational evidence provides a fairly robust measure of the entropy floor for the diffuse hot gas in groups (Lloyd–Davis et al. 2000) of 100 KeV/cm^2. A related, very important measurement is the fraction of baryons that has been converted into a "cold", non X–ray emitting phase (i.e stars and neutral hydrogen). This constraint is crucial as it defines the amount of energy available from SNe and the importance of cooling in groups and clusters (Renzini 2000). Balogh et al. (2001) estimate that only a small fraction (5–10%) of baryons has been converted into stars, almost independently of the total virial mass of the cluster.

3. Q: What are the physical processes that could affect the L–T relation?

• *Gas cooling.* At the center of groups the cooling time is much shorter than a Hubble time. Cooling would remove low entropy gas transforming it into stars and possibly originate the entropy floor observed. While advocated on the ground of its simplicity (Muanwong et al 2001 also Voit & Bryan 2001), the amount of gas involved cannot exceed the observed fraction of 5–15% of the total baryon fraction.
• *Energy injection from AGNs* (e.g Böhringer, this proceedings) would be an important source of heating. Most of the energy would come from jets that would carve "bubbles" in the ICM (Mc Namara et al 2001, Quilis et al. 2001), while the X-ray emission from the central engine in radio quiet QSOs would likely have a small effect due to the small cross section for the process.
• *Energy injection from SNe.* Winds propelled by SNe explosions (an hefty 10^{51}erg/SN) would transfer heat to the ICM, possibly escaping the halos of individual galaxies in the forming protocluster and enrich the ICM with metals. (Note: substantial metal enrichment could originate also from ram pressure and tidal stripping of galaxies (Moore, Quilis & Bower 2001).

4. Q: What are the most used theoretical tools to study the L–T relation?

• *Analytical methods* allow a fast exploration of parameter space, but must sometimes rely on the parametrization of the end results of complicated physical processes. While this approach requires studying the physics of gas in a somewhat idealized situation (spherical collapse, accretion from a uniform background) the amount of insight gained is impressive, although conclusions sometimes differ widely (Kaiser 1991,Valageas & Silk 1999, Tozzi & Norman 2000, Bryan 2000, Balogh, Babul & Patton 1999, among many). The most refined methods are based on the standard machinery developed to link gravitational clustering in Cold Dark Matter Models and the physics of gas and star formation (Cole

et al. 2000, Somerville & Primack 1999, Bower et al. 2001, Menci & Cavaliere 2000, Cavaliere, Giacconi & Menci 2000).
•*N-body simulations* are a powerful method, able to treat the highly non–linear problem of the formation of cosmic structures with very few assumptions. Recent observational evidence for a mono phase ICM (Böhringer et al 2001) remove some potential worries about the use of SPH methods, which do not describe well a multiphase medium. Some recent works on the L–T relation including feedback and star formation (Metzler & Evrard 1994, Bialek, Evrard & Mohr 2001, Borgani et al 2001b, Valdarnini 2001) provide a good starting point and an extensive list of references to the subject of simulations of galaxy clusters.

5. Q: Heating, Cooling or both?

As mentioned above, several papers suggested that simply the addition of cooling would remove enough gas from the ICM to reconcile models with the observed L–T relation. This would likely be in contrast with observational evidence that points to a limited fraction of baryons in clusters in a "cold" non X–ray emitting phase. Moreover it would be difficult to hide the large quantity of cooled gas in "dark baryons" as they would cause detectable deepening of the central potential well at the center of clusters (e.g Lewis et al. 1999, Valdarnini 2001). This would have a substantial effect on the predicted M–T relation increasing the emission weighted temperature of groups (Finoguenov et al 2001). On the other hand recent theoretical works, both analytical and numerical seem to (perhaps slowly) converge to a required energy input comparable to 100% of what is available from SNe (Kravtsov & Yepes 2000, Bower et al 2001, or even a few times higher (Borgani et al. 2001b, Valageas & Silk 1999, Wu, Fabian & Nulsen 2000) to satisfy the L–T relation. While semi-analytical models estimate the energy available from SNe to be of the order of ~ 0.25 keV per particle , Renzini (2000) suggested an even smaller energy budget available from SNe: just 0.1 keV. Taken together these works suggest that the required energy must be provided by both SNe and AGNs, perhaps active as major mergers shape the early type population of cluster galaxies. Unfortunately none of the N–body simulations cited above (some analytical works did) treated *both* cooling and heating in a fully consistent way or included the effect of AGNs on the ICM. This leaves the quantitative contribution of cooling and heating rather uncertain.

6. Q: Is there a preferred epoch for heating the ICM?

Not really. As the entropy S depends on a inverse power of ρ it might seem more efficient to heat the ICM at lower z (say z< 5) as suggested in Tozzi & Norman (1999). However, in their model the authors heated the gas *before* accretion, while at the background density. In a more realistic case gas will be heated when already inside halos that will later merge to form the cluster. While this requires more energy for a given entropy S, (ρ is higher by a factor ~ 200) this is more than compensated by the fact that halos collapsed at high z will form the core of the cluster at lower z (Governato et al. 2001), i.e. you dump energy right where it is needed. Borgani et al (2001b, 2001c) and Bialek, Evrard & Mohr (2000) tried a large range of z (1 to 5 and 20 respectively) finding a weak

dependence on results for the argument given above. Of course, a redshift too close to z ∼1 for heating would cause the L–T to evolve significantly at moderate redshift, contrary to observations.
Bottom line: it is very likely that a combination of cooling & feedback will give the correct, non–evolving L–T relation, although only stronger observational constraints and more refined simulations will allow us to evaluate the *quantitative* role of cooling, SNe and AGNs.

7. Future Improvements:

Numerical simulations including a treatment of hydrodynamical processes have reached a high degree of maturity, with widely different codes giving comparable results (Frenk et al 1999). However, the number of particles used to simulate *individual* halos is still systematically lower than in DM only runs (e.g Ghigna et al. 2001). The hot debate on the shape of inner density profiles in DM halos has started a race to higher resolution runs (Governato, Ghigna & Moore 2001). While the quest for the ultimate density profile of DM halos might ultimately prove futile it has sparked a number of improvements on codes and, equally important, increased the robustness of results. A key method is the so called "renormalization technique" (Katz & White 1993) where a halo taken from a cosmological simulation is resimulated at much higher resolution, while sparsely resampling the surrounding region. Fig.1 shows the crucial effect of increasing resolution on a sample of SPH simulations of renormalized halos. (Borgani et al 2001b,c). The L–T relation obtained from simulations of large cosmological volumes (where particle number and the ratio softening/R_{vir} for each halo depends on its virial mass) likely suffer of systematic biases due to the worsening resolution for less massive halos: namely smaller L_x and slower cooling due to lower central densities.

This is my very personal wish list for future theoretical and observational studies on the subject:

• Estimates of L_X and T in groups that exclude contamination from AGNs.
• Estimates of the amount of metals in clusters to a significant fraction of R_{vir} as another method to infer the energy release from SNe (Renzini 2000, De Grandi & Molendi 2001).
• A robust estimate of the fraction of "cold" baryons which keeps into account the amount of intracluster stars. Recent claims (see Arnaboldi et al 2001) based on intracluster PNs almost double the the efficiency of star formation in clusters.
• Simulations of sufficient resolution to treat cooling and star formation processes in a robust way. (note: robust does not mean realistic, but it's a start).
My checklist for simulating an individual cluster:

$N>10^5$
$\epsilon/R_{vir} < 1\%$
$N_{gas}(r < R_{vir}) > 10^5$
Simulation box $\sim$ 100Mpc
$N_{steps} >> 10^{3-4}$

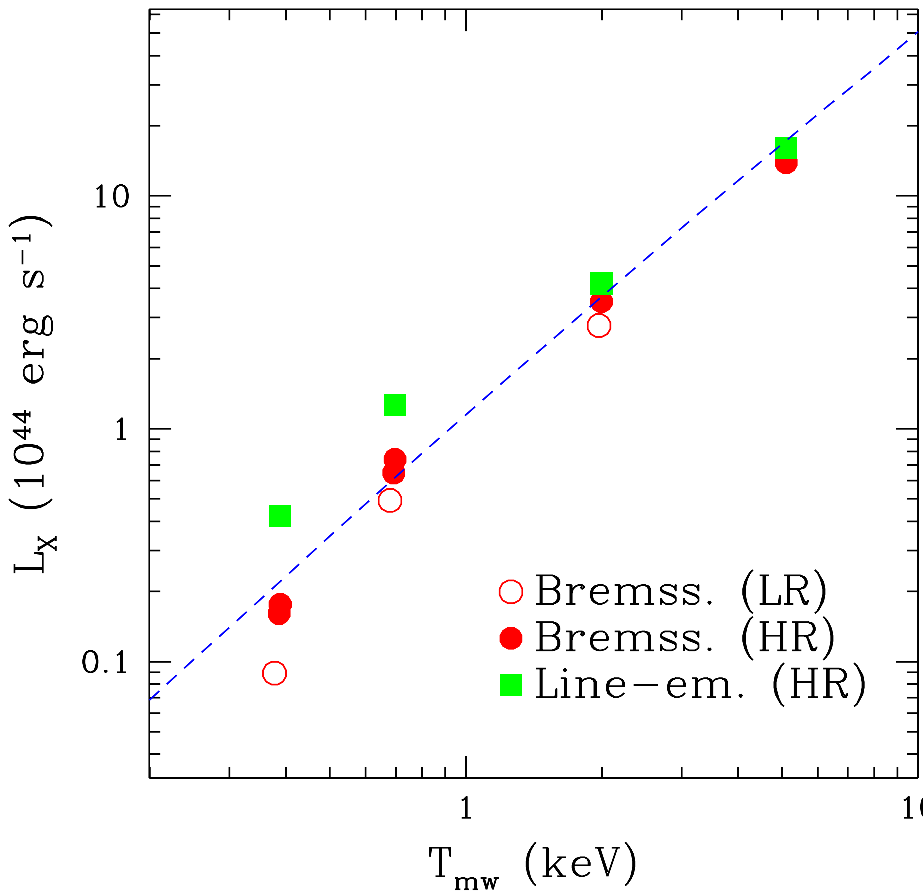

Figure 1. X-ray luminosity vs mass weighted Temperature: effects of resolution. Empty (red) dots are runs with ~ 0.5–2×10^4 gas particles within R_{vir}. Full dots are halos simulated with $N_{gas}(r > R_{vir}) \sim 10^5$. Softening is 1%$R_{vir}$. The upper filled (red) dots show the effect of having instead $\epsilon = 0.5\%$ R_{vir}: L_x grows by 15–20%. (Green) filled squares show the large effect of including line emission in the estimate of X–ray luminosities for the high res runs. The dashed line is the scaling predicted by Kaiser (1986) assuming NFW (Navarro, Frenk & White 1995) profiles. (data from Borgani et al. 2001 in prep.)*Bottom line: use at least 10^5 gas particles per halo to avoid nasty systematic effects like reproducing a bend in the L–T relation at $T < 0.3$ KeV. Correct for line emission if you compare vs. real data.*

• Exploring the role of QSO's and AGNs in heating the ICM in a cosmological context.
• Introducing heating schemes that closely follow the time evolution of the physical process behind it.
• Resolving the discrepancy between adiabatic runs with mesh and SPH codes (e.g Kravtsov et al. 2001, also Springel & Hernquist 2001 and Cen & Ostriker 1999) : why SPH simulations do not have an entropy floor and mesh codes do?

Acknowledgments. I wish to thank Stefano Borgani, Marino Mezzetti and Riccardo Valdarnini for organizing such an interesting and lively meeting and Uros Seljak and Bepi Tormen for stimulating discussions (although they made me skip a coffee break or two). I also thank my collaborators Stefano Borgani, Nicola Menci, Tom Quinn, Joachim Stadel, Paolo Tozzi & James Wadsley for allowing me to discuss our results and show Fig.1. in advance of publication.

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